ARMY RESEARCH LABORATORY

A Computational Study of Laminate Transparent Armor Impacted by FSP

by C. G. Fountzoulas, B. A. Cheeseman, P. G. Dehmer, and J. M. Sands

ARL-RP-249 **June 2009**

A reprint from the *Proceedings of the 23rd International Symposium on Ballistics*, Vol. II, pp. 873–881, Tarragona, Spain, 16–20 April 2007.

NOTICES

Disclaimers

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5069

ARL-RP-249 **June 2009**

A Computational Study of Laminate Transparent Armor Impacted by FSP

C. G. Fountzoulas, B. A. Cheeseman, P. G. Dehmer, and J. M. Sands

Weapons and Materials Research Directorate, ARL

A reprint from the *Proceedings of the 23rd International Symposium on Ballistics*, Vol. II, pp. 873–881, Tarragona, Spain, 16–20 April 2007.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
June 2009	Reprint	April 2007

4. TITLE AND SUBTITLE
A Computational Study of Laminate Transparent Armor Impacted by FSP

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
C. G. Fountzoulas, B. A. Cheeseman, P. G. Dehmer, and J. M. Sands

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-WM-MD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-RP-249

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
A reprint from the *Proceedings of the 23rd International Symposium on Ballistics*, Vol. II, pp. 873–881, Tarragona, Spain, 16–20 April 2007.

14. ABSTRACT
The current report reports on our efforts to simulate the ballistic impact of a fragment simulating projectile (FSP) into a Lexan 9034 polycarbonate (PC)- polymethylmethacrylate (PMMA), which was a Plexiglas G manufactured by Atofina Chemicals, - Lexan 9034 Polycarbonate laminate system, with and without the presence of polyurethane adhesive, using the nonlinear analysis software AUTODYN. The simulation results, which included V_{50} measurements, were compared to the ballistic results from the experiments of Hsieh et al [1], on targets consisting of 3mm PC-12mm PMMA-3mm PC impacted by 17-gr, 0.22 caliber fragment simulating projectile (FSP) at impact velocities ranging from 173, 475, 846 and 1004 m/s.

Our simulations of the impact of a 0.22-cal FSP projectile against the above laminated target showed that the existing material models were not able to reproduce the ballistic behavior of the PC-PMMA-PC target for transparent armor applications. However, the reproduction of the cracks in the PMMA and the predicted V_{50} impact velocity was achieved by modifying the existing material models of PMMA by adding a material strength model and a failure criterion. The necessary parameters of the chosen strength and failure models were obtained from published data. Our simulation showed that the presence of the polyurethane provide an additional resistance to penetration, as it is witnessed by the experimentation. The simulation results and the effectiveness of the modifications of the existing PMMA material models will be discussed in detail.

15. SUBJECT TERMS
laminate, transparent armor, FSP, impact, BOS, strength and failure models

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					C. G. Fountzoulas
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (*Include area code*)
Unclassified	Unclassified	Unclassified	UU	14	410-306-0844

A COMPUTATIONAL STUDY OF LAMINATE TRANSPARENT ARMOR IMPACTED BY FSP

C. G. Fountzoulas[1], B. A. Cheeseman[1], P. G. Dehmer[1] and J. M. Sands[1]
[1] U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069
Tel: (410) 306-0844, Fax: (410) 306-0806
cfount@arl.army.mil, *bcheeseman@arl.army.mil*, *pdehmer@arl.army.mil*,

The current paper reports on our efforts to simulate the ballistic impact of a fragment simulating projectile (FSP) into a Lexan 9034 polycarbonate (PC)-polymethylmethacrylate (PMMA), which was a Plexiglas G[1] manufactured by Atofina Chemicals, - Lexan 9034 Polycarbonate laminate system, with and without the presence of polyurethane adhesive, using the nonlinear analysis software AUTODYN. The simulation results, which included V_{50} measurements, were compared to the ballistic results from the experiments of Hsieh et al [1], on targets consisting of 3mm PC-12mm PMMA-3mm PC impacted by 17-gr, 0.22 caliber fragment simulating projectile (FSP) at impact velocities ranging from 173, 475, 846 and 1004 m/s.

Our simulations of the impact of a 0.22-cal FSP projectile against the above laminated target showed that the existing material models were not able to reproduce the ballistic behavior of the PC-PMMA-PC target for transparent armor applications. However, the reproduction of the cracks in the PMMA and the predicted V_{50} impact velocity was achieved by modifying the existing material models of PMMA by adding a material strength model and a failure criterion. The necessary parameters of the chosen strength and failure models were obtained from published data. Our simulation showed that the presence of the polyurethane provide an additional resistance to penetration, as it is witnessed by the experimentation. The simulation results and the effectiveness of the modifications of the existing PMMA material models will be discussed in detail.

INTRODUCTION

Commercially available transparent armor systems are utilized in a variety of military and civilian applications including face shields, goggles, vehicle vision blocks, windshields and windows, blast shields, and aircraft canopies [1]. High performance transparent armor systems typically consist of several different materials, such as polymethyl methacrylate (PMMA), float or soda lime glass and polycarbonate (PC) bonded together with a rubbery interlayer such as polyurethane (PU) or polyvinylbutyral (PVB). Other advanced transparent systems can contain

---

[1] Plexiglas G is a Registered Trademark of AtoHaas N.A., Inc.

more exotic transparent armor materials such as sapphire, ALON or spinel. The lamination sequence, material thicknesses and bonding between layers has been shown to drastically affect system performance and it has been observed that each material serves an important function. Over the years there have been numerous developmental efforts to optimize the ballistic performance of lightweight, multi-layered transparent armor systems. The majority of these efforts are experimental, which can be time consuming and costly. More recently, numerical simulations coupled with experiments have been reported to provide a more cost-effective way of studying the ballistic performance of laminated transparent armor systems [2-7]. Additionally, numerical simulations provide insight into the material response and failure mechanisms that occur in the transparent laminates during the impact process. However, ten years ago in their review of the status of simulation the impact of transparent armor, Brockman and Held [8] noted that the weakness in simulating impact into transparent armor was the lack of adequate material models and the corresponding material characterization data required by them. Since then, efforts in the development of material models suitable for simulating the impact into these materials have been reported and some high strain rate characterization required by the models has been published (although there is a dearth of information regarding others).

As computational power increases and numerical analysis techniques mature, models that can accurately describe the response and failure behavior of transparent materials undergoing large deformations and failure at high strain rates are essential. When simulating such dynamic events, the material response is typically described by (1) an equation of state (EOS) which relates the density (volume), internal energy and temperature of the material to pressure; (2) a constitutive relationship which describes the strength of the material to resist distortion; and (3) a failure model that can describe the failure of a material under a multiaxial stress state at various strain rates. Although a comprehensive review of all the material models that have been formulated and could be utilized in modeling the materials used in transparent armor is beyond the scope of the current effort, the present work will review the material models that have been utilized for the analysis of transparent armor materials.

Polymeric transparent armor materials include cast PMMA, polycarbonate, polyurethane, extruded PMMA and rubbery interlayers such as polyurethane and PVB. When laminated in appropriate combinations, these materials provide some of the most mass efficient transparent armors available. However, accurately simulating these materials over a range of strain rates has proven challenging. Recent efforts have modeled PC using an isotropic, elastic-plastic material model having a strain rate dependent yield stress in LS-DYNA by Nandlall et al.[3,4] and in Abaqus/Explicit by Sarva et al [9]. PC has also been modeled using a shock EOS, and a piecewise linear strength model that incorporated both strain and strain rate hardening [5]. A nonlinear viscoelastic-viscoplastic material model was developed by Frank, G.J. and Brockman, R.A [10] for glassy polymers such as acrylics and PC. The model was further refined to combine nonlinear viscoelasticity and viscoplasticity into a set of equations suitable for multi-axial loadings and extended to incorporate the effects of hydrostatic pressure [11]. PMMA as been recently modeled using a rate dependent elastic-viscoplastic model

by Sarva et al [8], and Mulliken [12]. According to Brockman and Held [8] the material modeling situation for interlayer materials (PU and PVB), which can be considered incompressible and viscoelastic, is poor. Many finite element impact codes contain models for incompressible materials, and models for viscoelastic materials, but not for viscoelastic materials which are incompressible. Livingstone et al. [5] modeled the PU as elastic with a principle tensile stress failure criterion. While not a study of transparent armor, Zaera et al. [13] investigated the effect of the adhesive layer in composite armor. In this study, the researchers considered the polyurethane as viscoelastic and determined the constants utilized from the Split Hopkinson Pressure Bar (SHPB) experiments.

For simulations that have been done which incorporate glass, the Johnson-Holmquist (JH) strength and failure model which was developed for brittle materials has typically been utilized with reasonable success. Constants for float glass were derived and reported in [14]. The JH model has proven accurate in simulations of impact into various ceramics and although there have been some discrepancies noted when simulating the conchoidal crater formation in glass[15], it has generally given accurate results for the ballistic impact into glass. The authors know of no simulations of the impact into ALON, spinel or sapphire.

Although good correlation has been reported between experiments and simulations of transparent armor, a number of areas require further development. One such area is the response of polymeric materials to shock loading. Millett et al. [16] have noted, with the exception of PMMA which is used as a window material in plate impact experiments, there is a scarcity of experimental data. In addition, while the utilization of viscoplastic strength models for polycarbonate is fairly mature, PMMA and PU strength modeling efforts appear to have lagged. Similarly, development of a failure criterion for polymers under high pressures and multi-axial stress states appears to be a research task. Similarly, while the phenomenological JH model provides good results for most glass, advanced transparent materials such as sapphire, ALON and spinel have not been characterized for any particular material model. While much has been done to yield accurate simulations, much is left to do. Recognizing the limitations with the current material models, the authors will utilize these and several numerical techniques to investigate the impact of an FSP into a laminate armor configuration described below. The current effort will present some results of an ongoing review some of the models utilized for recent results of impact simulations into transparent armor materials. In addition, some numerical studies will be performed to investigate several different analysis techniques to qualitatively determine their accuracy when compared with experiments of Hsieh et al [1]. The study will conclude with an assessment of the numerical techniques and material models applicable for the high strain rate behavior of transparent materials

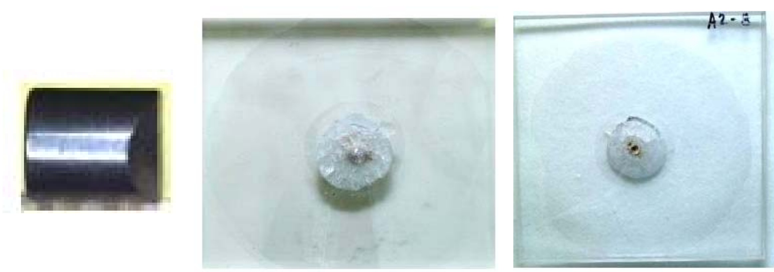
EXPERIMENTAL DETAILS

Ballistic measurements were carried out at using a 17-gr, .22-cal, FSP (Figure 1(a)) and are detailed in Hsieh et al. [1]. The target laminates, 3-mm PC/1-

mmPU/12-mm PMMA/1-mm PU/3-mm PC, were C-clamped at all four corners to a heavy steel test stand having a 12 mm-diameter opening in the center. The testing was conducted using a powder gun having a 0.56-m-long, 5.66-mm barrel with a 1:12 twist. The muzzle of the gun was placed 2.5 m from the target fixture. All shots were conducted with the target normal to the projectile line of flight, i.e., 0° obliquity. During the ballistic measurements, the amount of smokeless powder that was loaded into the brass case was varied to control the projectile velocity. Figures 1b-c show the fracture pattern of the PC-PMMA-PC laminated target.

NUMERICAL SIMULATIONS

The numerical modeling was carried out using the nonlinear analysis commercial software AUTODYN. To reproduce the failure of the laminate target impacted by a 0.22-cal FSP three dimensional axisymmetric models using smooth particle hydrodynamics (SPH). This was done by simulating projectiles impacting the targets of Hsieh et al. [1] at the experimental velocities of 173, 475, 846 and 1004 m/s. The dimensions of the models were equal to the dimensions of the actual target. To study the effect of the polyurethane layer, we modeled the laminate targets with and without PU. In our previous work [2] we determined that when the PMMA is modeled using the existing in AUTODYN library material models the V_{50} was 385 m/s, significantly smaller of the experimentally determined 846 m/s. We also were not able to reproduce the cracks produced in the PMMA of the actual target.



(a) (b) (c)

Figure1: (1a) 0.22-cal, FSP; (1b) Typical conoid fracture pattern observed in the exit side of the PC-PMMA-PC. (1c) Typical fracture pattern of the PC-PMMA-PC laminate after impact with the 0.22-cal FSP [1]

The material models utilized for the PC, PU and steel were obtained from the AUTODYN material library. The PC was modeled using a shock EOS, piecewise Johnson-Cook (JC) strength model and a plastic strain failure criterion; the PU, a linear EOS, and a principle stress failure criterion; and the steel modeled using a shock EOS and a JC strength model. However, the PMMA was modeled on the one hand using a shock EOS, no strength and no failure criterion from the AUTODYN material library; and on the other hand was modeled using the AUTODYN shock EOS and introducing a von Mises strength model and a principle

stress failure criterion with crack softening criterion. The shear modulus and the yield stress for the Von Mises strength model were obtained from the work of Nandlall et al. [17]. The principal tensile failure stress was obtained from Moy et al. [18] and Weerasooriya et al. [19].

As it was expected the results from the simulations using the AUTODYN material models for PMMA were not able to reproduce the V50 of 846 m/s reported by Hsieh et al [1]. At 846 m/s the projectile penetrated the target. However, the introduction of von Mises strength model and the failure criterion to the existing in AUTODYN material model reproduced the failure in the PMMA and predicted correctly the 846 m/s V50. Figures 2 to 7 show clearly the crack reproduction in the PMMA and the velocity profile at 846 m/s impact velocity. Figure 8 shows the experimental results at various impact velocities published by Hsieh et al. [1].

The failure response of the laminate target without the PU interlayer was different than the failure response with interlayer (Compare Figure 5, and Figure 10). The simulations with PU, which acts like an impendence layer between the PMMA and PC, did not show any cracking of the PC, as it was expected. Certain simulations without PU interlayer showed faster penetration of the target; however, further investigations are currently being conducted.

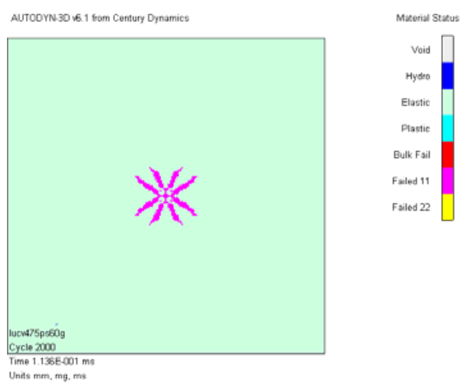


Figure 2: Simulated impact at 475 m/s

Figure 3: Experimental impact at 475 m/s

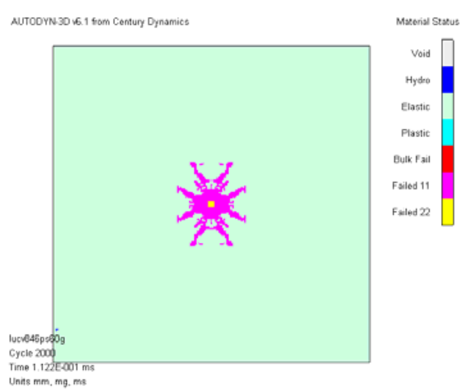


Figure 4: Simulated impact at 846 m/s

Figure 5: Experimental impact at 846 m/s

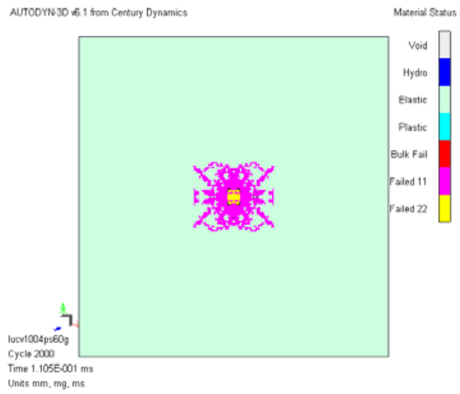


Figure 6: Simulated impact at 1004 m/s

Figure 7: Experimental impact at 1004 m/s

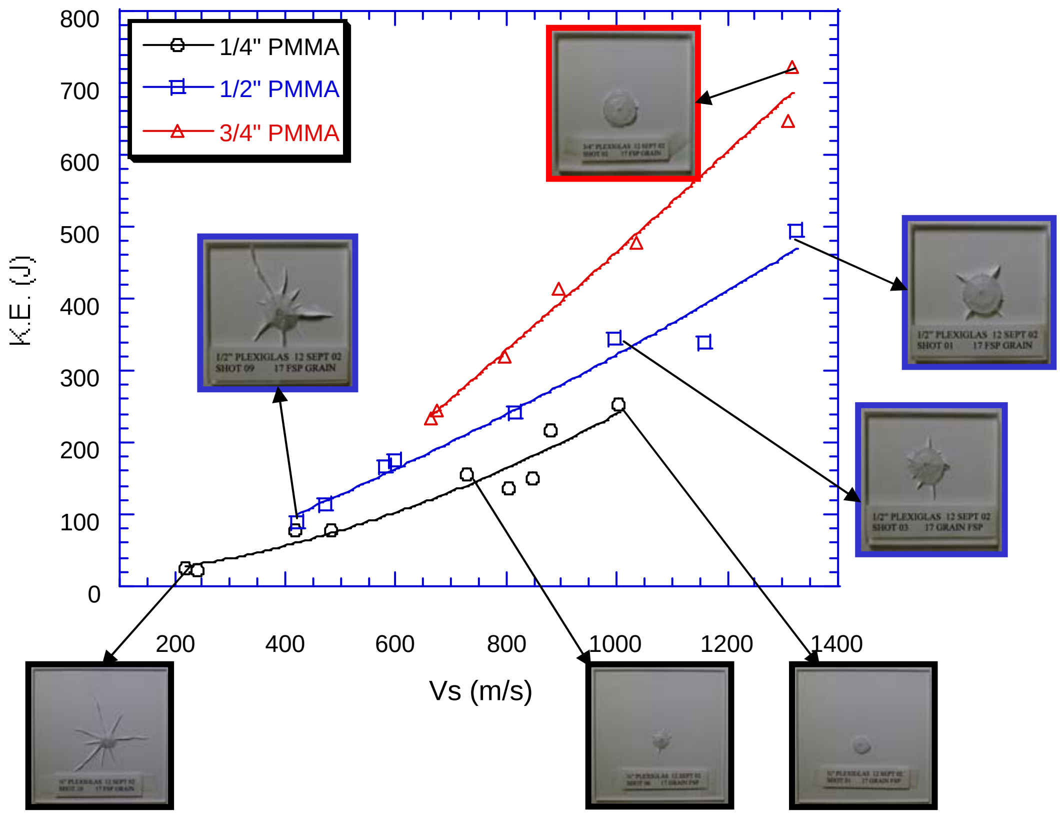


Figure 8. Plots of ballistic energy values as a function of striking velocity obtained for the monolithic PMMA of various target thicknesses against the 0.22-cal FSP impact; insert show the corresponding mode of impact-induced failure; solid lines are the second-order polynomial curve fit for the corresponding data (Hsieh at al. [1])

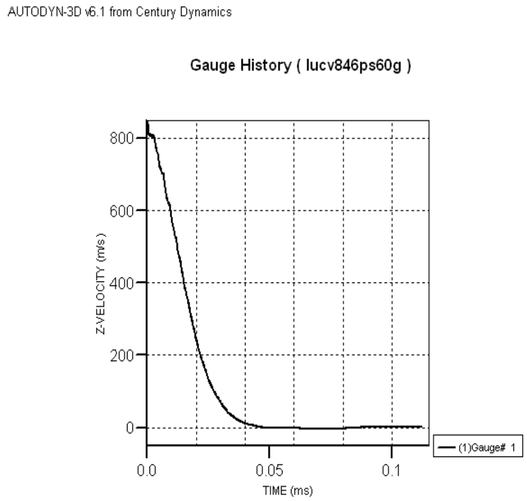


Figure 9. Velocity profile at 846 m/s

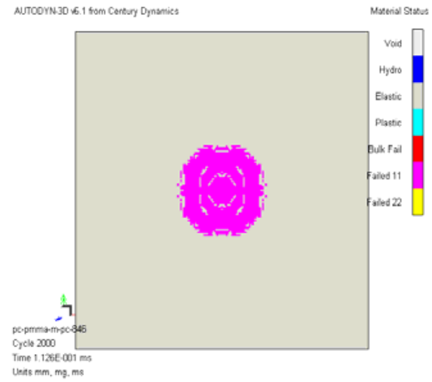


Figure 10. No PU. Impact at 846 m/s

DISCUSSION

To date, the development of transparent armor has been accomplished primarily through experiments and experience. However, recent advances in the numerical techniques and materials model have allowed the accurate simulation of the ballistic impact into multi-layer transparent armor configurations. Current simulations of the impact of a .22-cal FSP projectile against a laminated target have shown that the existing in the AUTODYN PMMA material model, when modified with the introduction of a von-Mises strength model and a principal tensile stress failure criterion reproduce the experimental cracks and predict the actual V50 of the ballistic test. The simulations that were performed with PU interlayer indicate that the presence of the polyurethane provide an additional resistance to penetration, as it is witnessed by the experimentation. Future studies will attempt to study this cracking using 3D models and by investigating existing failure and strength models. In addition, modeling of the polyurethane interlayer proved to be problematic due to limitations with the current numerical techniques.

CONCLUSIONS

The crack reproduction and the prediction of the V_{50} by simulation of the experimental data of a PC/PU/PMMA/PU/PC laminate [1] were achieved successfully by modifying the existing strength and failure models of PMMA in the AUTODYN materials library. The PMMA material model was modified by introducing a von-Mises strength model and a principal tensile strength criterion using published parameters [17-19].   Future studies will attempt to improve the prediction of the failure of the PMMA by simulation for various loading rates of PMMA and laminate geometries.

REFERENCES

[1] A.J Hsieh, D. DeSchepper, P. Moy, P. G. Dehmer, J. W. Song, *ARL-TR-3155*, February 2004.

[2] C.G. Fountzoulas, B. A. Cheeseman and J. M. Sands, "A numerical simulation capabilitiesin the impact analysis of laminate transparent armor", 3rd ICSSD, June 19-22, 2005, Kissimmee, Florida
[3 D. Nandlall, J. Chrysler, "*A numerical analysis of the ballistic performance of a 6.35mm transparent polycarbonate plate*" DREV-TM-9834, 1998.
[4] D. Nandlall, G. Pageau, D. Bourget, and Z. Gopaul, "*Numerical and experimental study of the ballistic resistance of polycarbonate armour systems*" 18th International Symposium on Ballistics, San Antonio, Texas, 15-19 November, 1999.
[5] I. Livingstone, M. Richards, R. Clegg. "*Numerical and experimental investigation of ballistic performance of transparent armour systems*" Lighweight Armour Systems Symposium, Royal Military College of Science, UK, 10-11 Nov. 1999.
[6] P. J. Hazell. and S. A. Armstrong, "*Perforation of spaced glass systems by the 7.62mm NATO ball round*" in the Proceedings of the 19th International Symposium of Balllistics, Interlaken, Switzerland, 7-11 May 2001.
[7] P. M. Kelly, "*Lightweight transparent armour systems for combat eyewear*" in the Proceedings of the 19th International Symposium of Balllistics, Interlaken, Switzerland, 7-11 May 2001.
[8] R. A. Brockman. and T. W. Held "*Transparency impact simulations: status and research issues*" in the Proceedings of the Conference on Aerospace Transparent Materials and Enclosures, v. II, WL-TR-94-4084, March 1994.
[9] S.. Sarva, A. D. Mulliken, M. C. Boyce, and A. J. Hsieh, "*Mechanics of transparent polymeric material assemblies under projectile impact: simulations and experiments*" in the Proceedings of the XXth Army Science Conference, Orlando, Florida, 2004.
[10] G. J. Frank. and R. A. Brockman, "*Constitutive models for rate-sensitive transparency materials*" in the Proceedings of the Conference on Aerospace Transparent Materials and Enclosures, v. II, WL-TR-94-4084, March 1994.
[11] G. J. Frank. and R. A. Brockman, "*A viscoelastic-viscoplastic constitutive model for glassy polymers*" Int. J. Solids and Struct., 38, 2001.
[12] A. D. Mulliken, "*Low to high strain-rate deformation of amorphous polymers: experiments and modeling*" M.S. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 2004.
[13] R. Zaera, S. Sanchez-Saez, J. L. Perez-Castellanos, and C. Navarro, "*Modelling of the adhesive layer in mixed ceramic/metal armours subjected to impact*" Composites: Part A, 31, 2000.
[14] T. J. Holmquist, J. R. Gordon, D. E. Grady, C. M. Lopatin, E. S. Hertel Jr., "*High strain rate properties and constitutive modeling of glass*", 15th International Symposium on Ballistics, Jerusalem, Israel, 21-24 May 1995.
[15] E. A. Taylor, K. Tsembelis, C. J. Hayhurst, L. Kay, M. J. Burchell, "*Hydrocode Modelling of Hypervelocity Impact on Brittle Materials: Depth of Penetration and Conchoidal Diamete*r", Int. J. of Impact Eng. **23** (1): 895-904 Part 2 DEC 1999.
[16] J. C. F. Millett, N. K. Bourne, and N. R. Barnes, "*The behavior of an epoxy resin under one-dimensional shock loading*" J. Appl. Physics, 92(11), 2002.
[17] G. Pageau, D. Nandlall, and M. Bolduc, "*A numerical analysis of the back plane transient deformation of a polycarbonate plate*", DREV-TR 1999-160, Research and Development Branch, Department of National Defence, Canada, February 2000
[18] P. Moy, T Weerasooriya, W. Chen and A. Hsieh, "Dynamic stress-strain response and failure behavior of PMMA", IMECE2003-43371, November 15-21, 2003, Washington D.C.
[19] T Weerasooriya, P. Moy, D. Casem, M. Cheng, and W. Chen "Fracture toughness of PMMA as a function of loading rate", Proceedings of the 2006 SEM Annual Conference on Experimental Mechanics, June 5-7, Louis, Missouri

NO. OF COPIES	ORGANIZATION
1 (PDF only)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB IMNE ALC HRR 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK PE 2800 POWDER MILL RD ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

1	DIR USARL AMSRD ARL CI OK TP (BLDG 4600)

NO. OF COPIES	ORGANIZATION
2	DARPA L CHRISTODOULOU J GOLDWASSER 3701 N FAIRFAX DR ARLINGTON VA 22217-5600
2	DIRECTED TECHNOLOGIES INC J PEREZ R SANDS 3601 WILSON BLVD STE 650 ARLINGTON VA 22201
1	US ARMY TARDEC AMSRD TAR R D TEMPLETON MS 263 6501 E 11 MILE RD WARREN MI 48397-5000
1	THE UNIV OF MISSISSIPPI A RAJENDRAN MECHL ENGRG 201B CARRIER HALL UNIVERSITY MS 38677-1848

ABERDEEN PROVING GROUND

NO. OF COPIES	ORGANIZATION
25	DIR USARL AMSRD ARL WM S KARNA J MCCAULEY J SMITH AMSRD ARL WM M J BEATTY R DOWDING S MCKNIGHT AMSRD ARL WM MA M VANLANDINGHAM AMSRD ARL WM MB M BERMAN T BOGETTI W DRYSDALE A FRYDMAN AMSRD ARL WM MC M MAHER AMSRD ARL WM MD B CHEESEMAN E CHIN P DEHMER G GILDE P PATEL J SANDS J YU AMSRD ARL WM TA C HOPPEL E HORWATH C KRAUTHAUSER S SCHOENFELD AMSRD ARL WM TD T WEERASOORIYA AMSRD ARL SL BG M ROTHWELL